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(54) SCANNING OPTICAL SYSTEM

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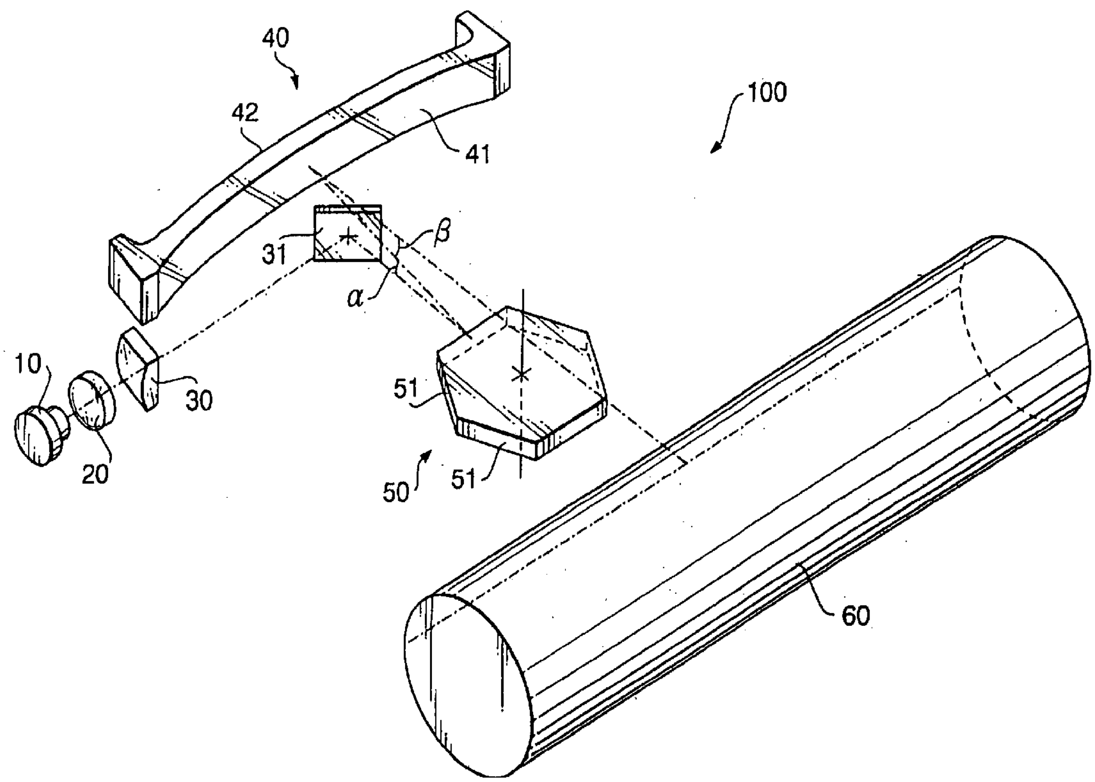
(57) **ABSTRACT**

A scanning optical system includes a light source including a multi-mode laser diode that emits a laser beam, and a polygonal mirror that deflects the laser beam emitted by the light source. An fθ lens converges the laser beam deflected by the polygonal mirror on an object to be scanned. The fθ lens includes at least one refractive lens and a diffractive lens structure formed on at least one surface of the at least one refractive lens, the diffractive lens structure being configured to compensate for chromatic aberrations provided by a refractive lens structure of the fθ lens.



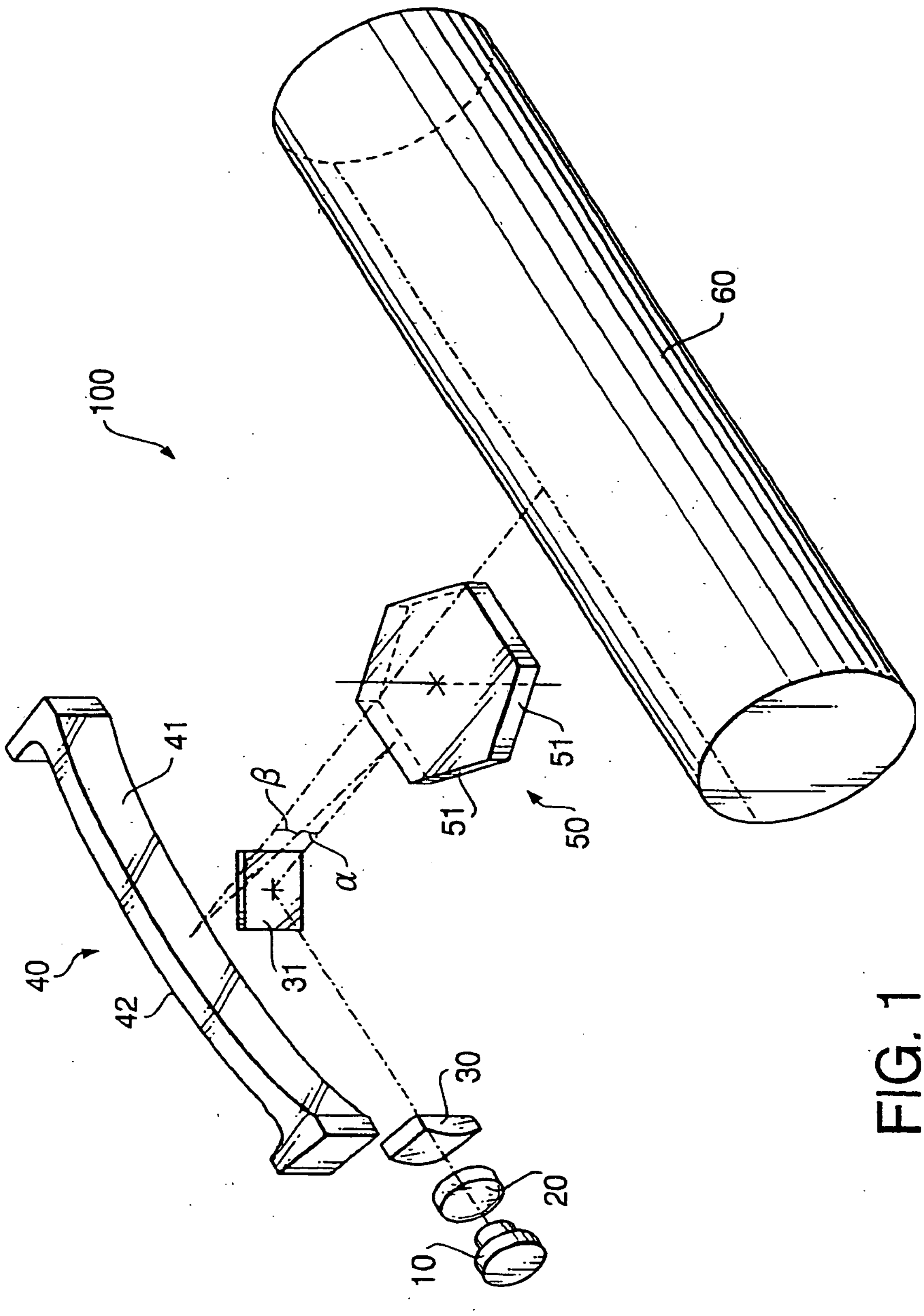


FIG. 1

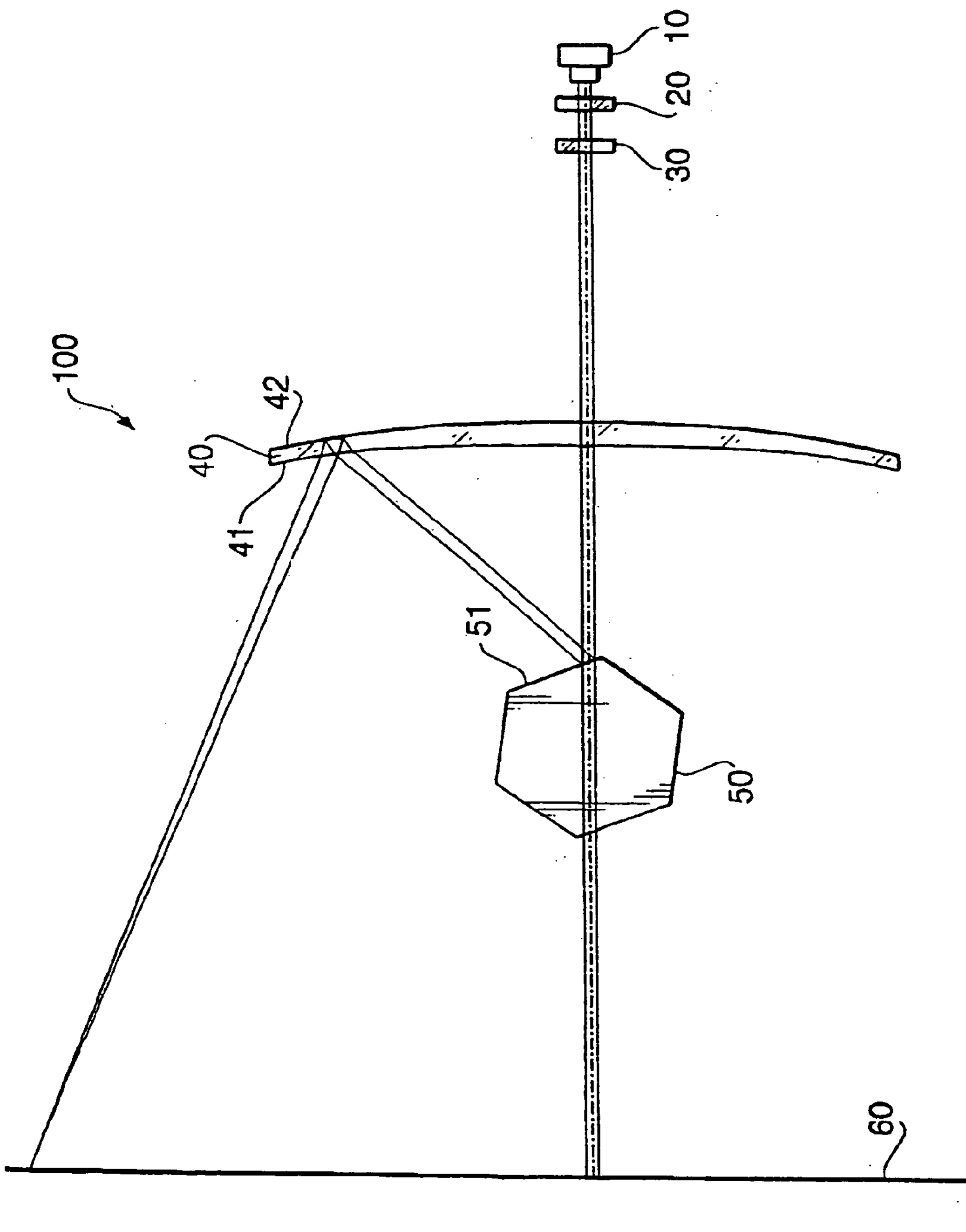


FIG. 2

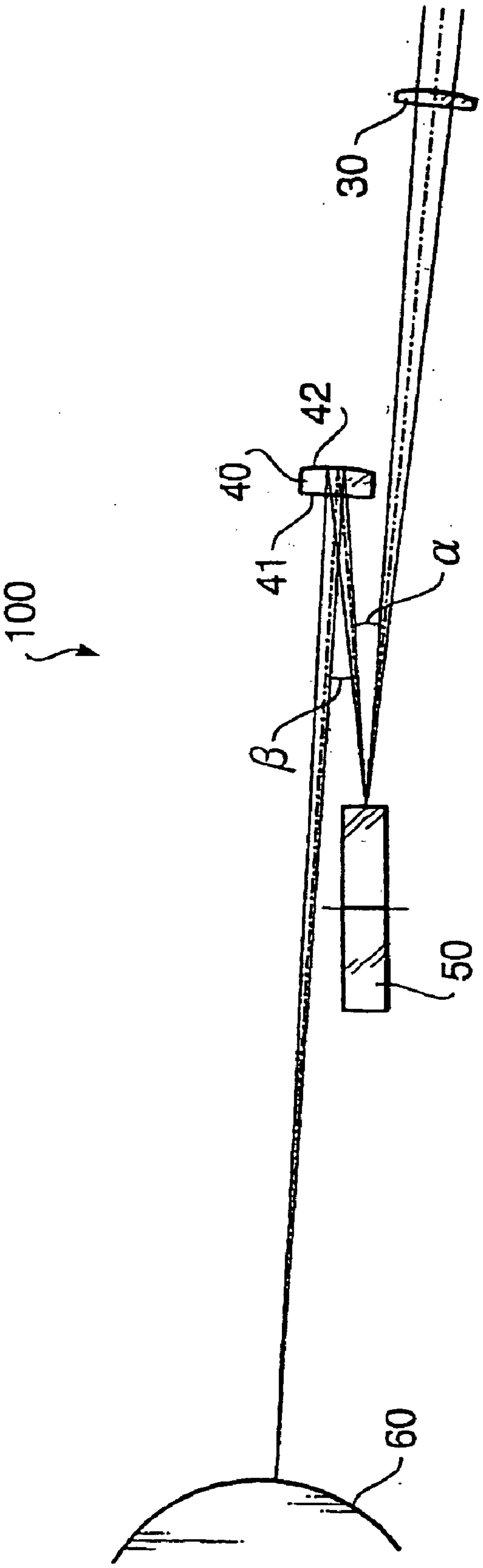
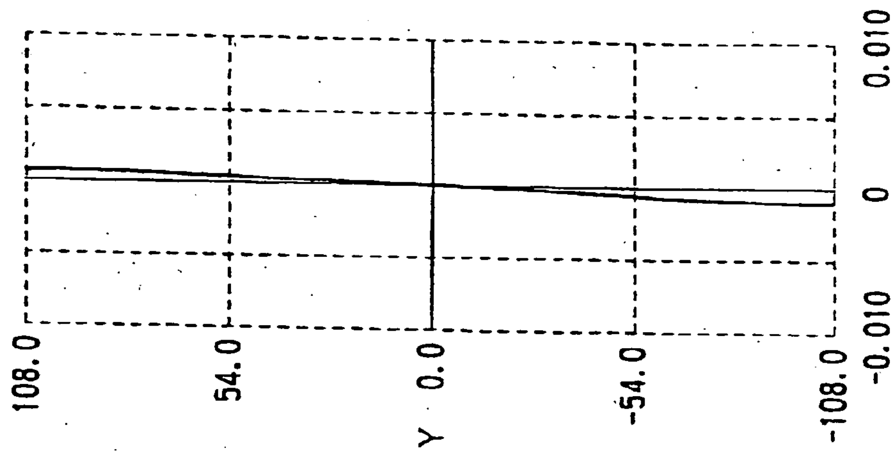
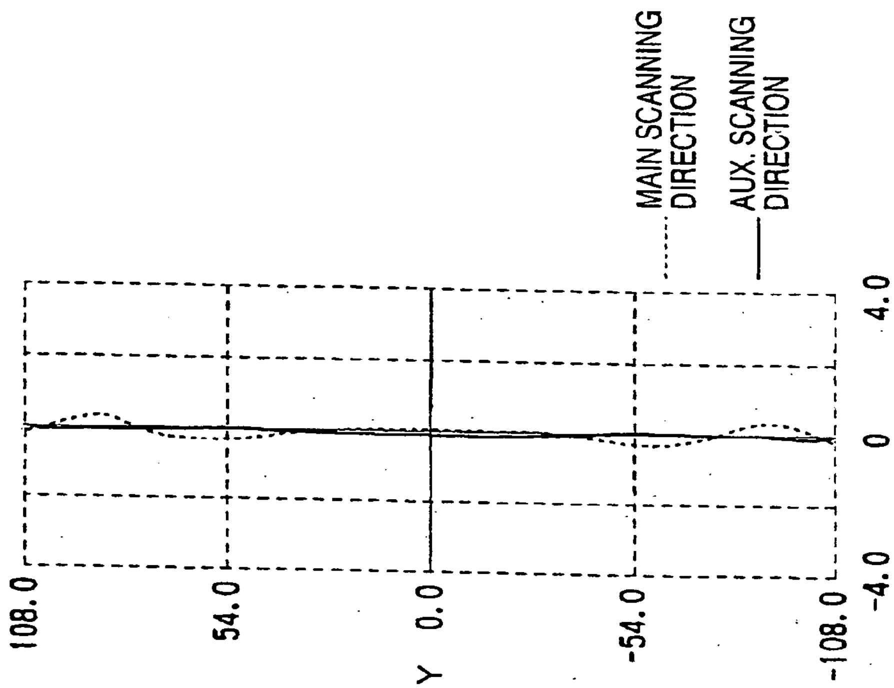


FIG. 3



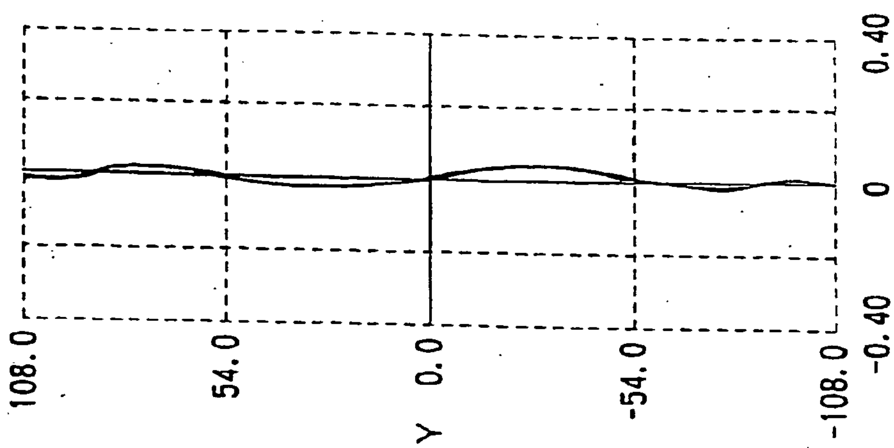
LATERAL CHROMATIC ABERRATION

FIG.4C



CURVATURE OF FIELD

FIG.4B



fθ ERROR

FIG.4A

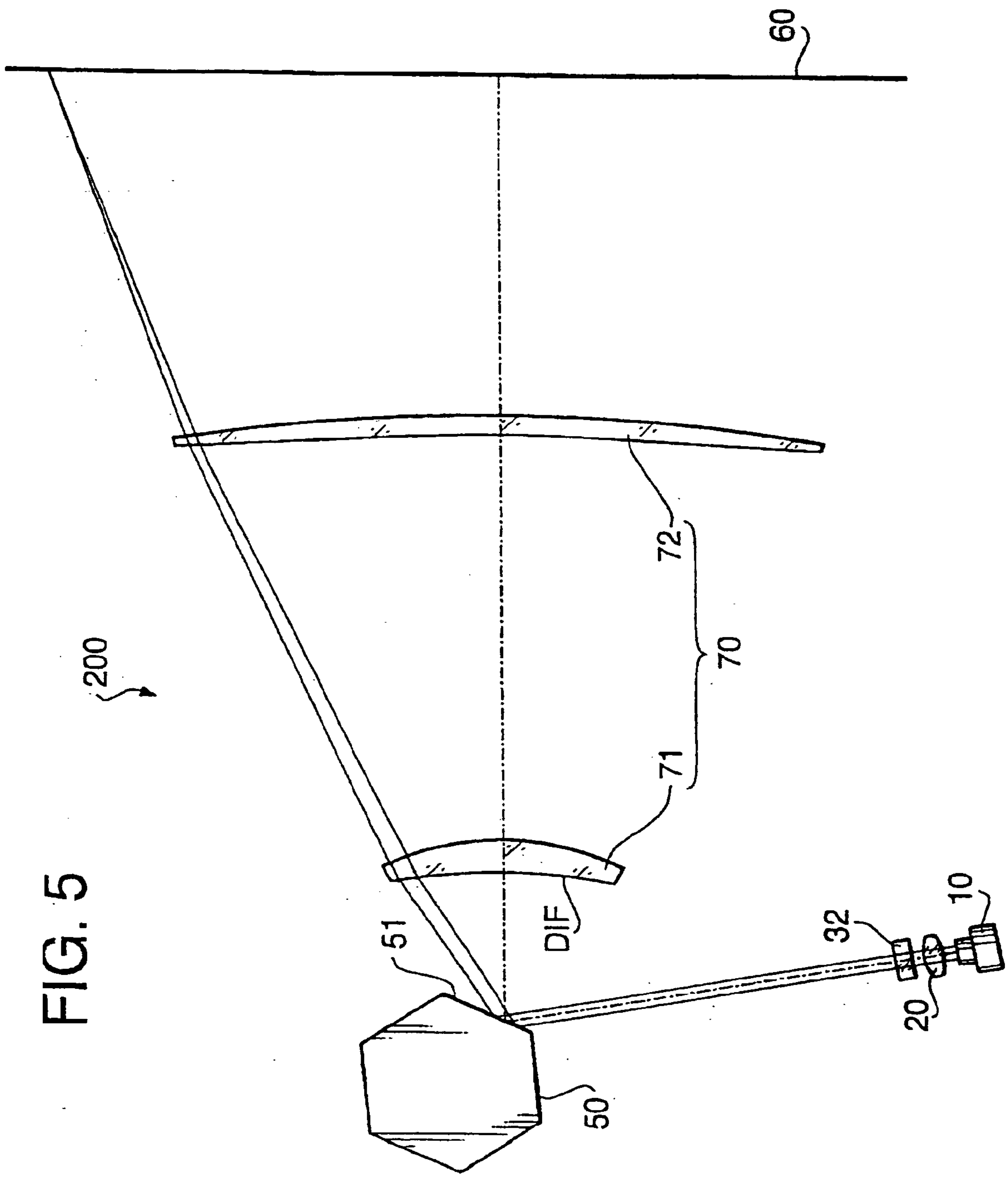


FIG. 5

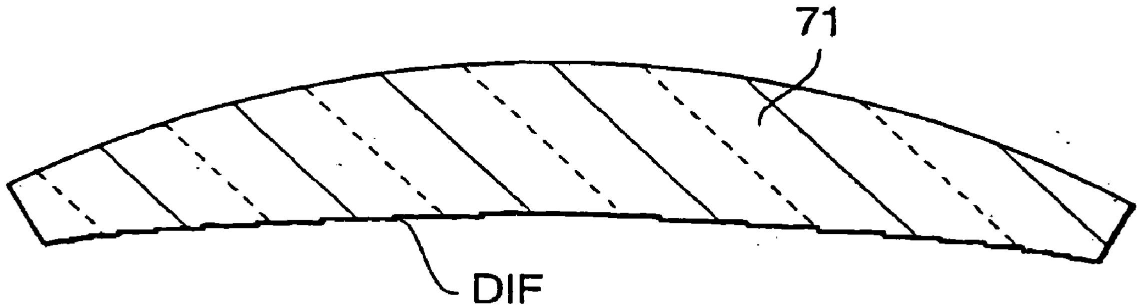


FIG.6A

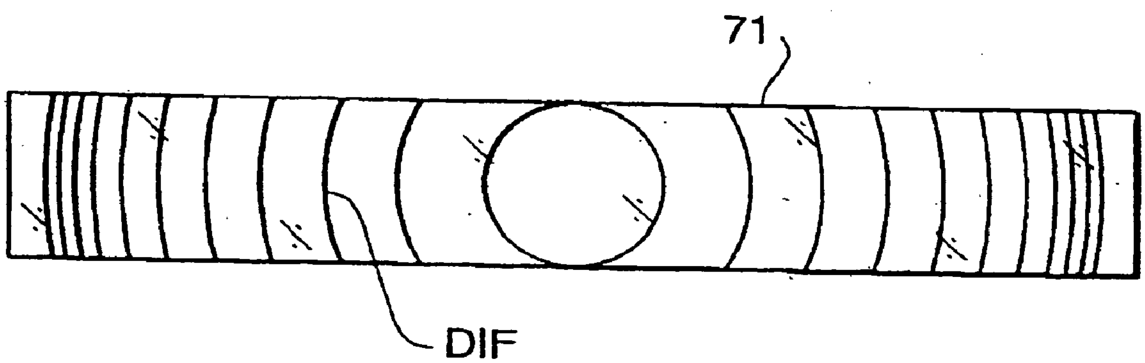


FIG.6B

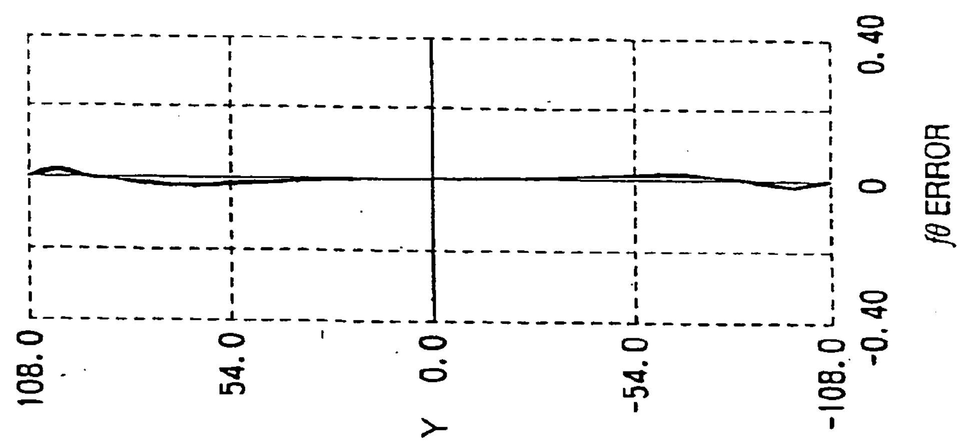


FIG.7A

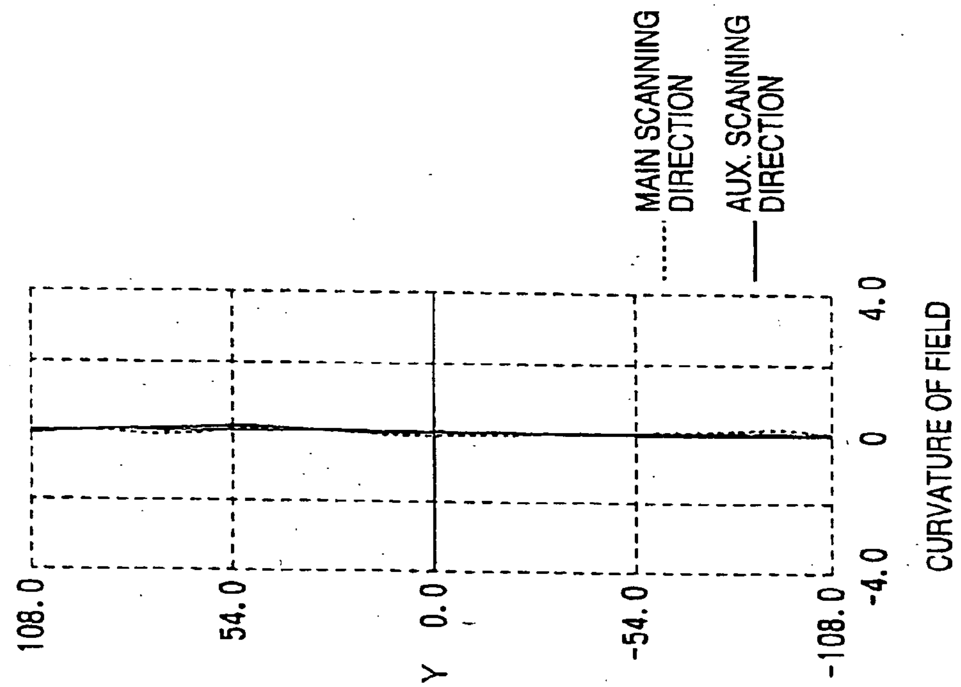


FIG.7B

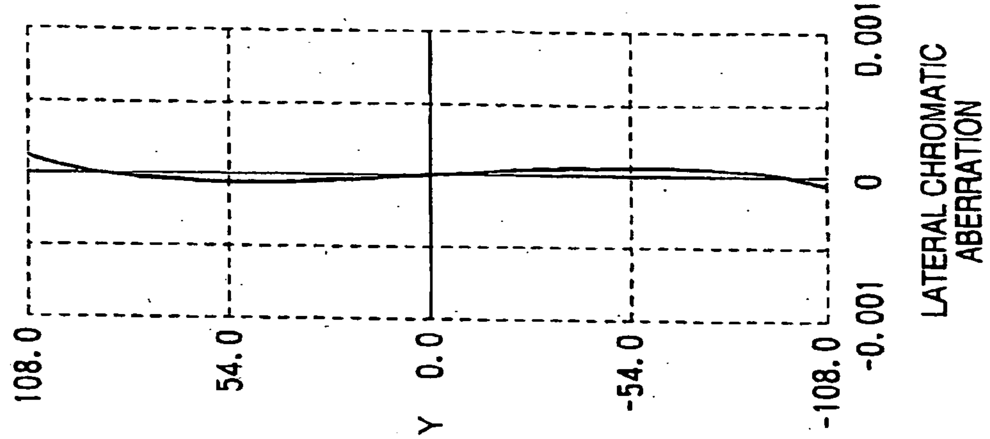


FIG.7C

SCANNING OPTICAL SYSTEM

[0001] This Application is a divisional application of pending U.S. patent application Ser. No. 10/322,531, filed on Dec. 19, 2002, the disclosure of which is expressly incorporated herein by references in its entirety.

BACKGROUND OF THE INVENTION

[0002] The present invention relates to a scanning optical system employed in an optical scanning unit for a laser beam printer or the like.

[0003] Typically, a scanning optical system is configured such that a laser beam emitted by a laser diode is deflected by a polygonal mirror to scan within a predetermined angular range. The scanning laser beam is converged by an fθ optical system on an object (which is generally a photoconductive surface) to be scanned, thereby a beam spot being formed on the object to be scanned. The beam spot on the object moves as the polygonal mirror rotates. By ON-OFF modulating the laser beam, an electrostatic latent image is formed on the photoconductive surface. In this specification, a direction where the beam spot moves on the object is referred to as a main scanning direction, and a direction perpendicular to the main scanning direction on the object surface will be referred to as an auxiliary scanning direction. In the following description, a shape and a power of each optical element will be described with reference to the directions on the object. For example, if an element is described to have a refraction power in the main scanning direction, whichever direction the element may be oriented, the power affects the beam spot in the main scanning direction on the object.

[0004] The scanning optical system is generally designed such that an optimum performance is achieved at a single design wavelength. A laser diode employed in such a scanning optical system is a single mode laser diode which emits a beam having a single wave length.

[0005] The single mode laser diode employed as a laser source of a conventional scanning optical system is more expensive than a multi-mode laser diode, which emits a beam having a plurality of peak wavelengths. Therefore, there has been a desire for making use of the multi-mode laser diode as the laser source so as to reduce a manufacturing cost.

[0006] The conventional scanning optical system is, however, designed on assumption of using a single wavelength as described above, and is not configured to compensate for lateral chromatic aberration. Therefore, if the multi-mode laser diode is used for the conventional scanning optical system, a size of the beam spot scanning on the photoconductive drum expands and thus a dot size of an image formed thereon is enlarged, which deteriorates a quality of the formed image.

[0007] It is apparent that if the optical system is configured such that the lateral chromatic aberration is compensated, the above problem does not occur even if the multi-mode laser diode is used. However, in order to compensate for the lateral chromatic aberration, a plurality of lenses made of different materials having different dispersions should be used. In such a configuration, even though the cost for the light source is reduced by replacing the single mode laser diode with a multi-mode laser diode, the entire cost of the optical system increases since the cost of the fθ lens increases.

SUMMARY OF THE INVENTION

[0008] The present invention is advantageous in that an improved scanning optical system is provided with which the manufacturing cost of the entire optical system can be reduced with employing the multi-mode laser diode as a light source.

[0009] According to an aspect of the invention, there is provided a scanning optical system, which is provided with a light source including a multi-mode laser diode emitting a laser beam, a polygonal mirror that deflects the laser beam emitted by the light source, and an fθ optical element that has positive power both in a main scanning direction and in an auxiliary scanning direction, the fθ optical element converging the laser beam deflected by the polygonal mirror to converge on an object to be scanned. In this scanning optical system, the fθ optical element is configured to have a reflection surface, the power of the fθ optical element in the main scanning direction being provided mainly by the reflection surface.

[0010] Since the power in the main scanning direction of the fθ optical element is mainly provided by the reflection surface, the lateral chromatic aberration can be well suppressed. Thus, with this configuration, the multi-mode laser diode can be used as the light source and a sufficient beam size can be achieved without increasing the manufacturing cost of the fθ optical element.

[0011] Optionally, the fθ optical element may include an element made of light transmissive material, the element having a first surface that transmits light and a second surface that reflects the light that enters into the element from the first surface.

[0012] Still optionally, the polygonal mirror and the fθ optical element are arranged such that the beam incident on the polygonal mirror and the beam deflected by the polygonal mirror forms a certain angle in the auxiliary scanning direction and that the beam incident on the fθ optical element and the beam reflected by the fθ optical element forms a certain angle in the auxiliary scanning direction.

[0013] According to another aspect of the invention, there is provided a scanning optical system which is provided with a light source including a multi-mode laser diode emitting a laser beam, a polygonal mirror that deflects the laser beam emitted by the light source, and an fθ lens that converges the laser beam deflected by the polygonal mirror on an object to be scanned. With this structure, the fθ lens is configured to include at least one refractive lens and a diffractive lens structure formed on at least one surface of the at least one refractive lens, the diffractive lens structure being configured to compensate for chromatic aberrations provided by refractive lens structure of the fθ lens.

[0014] With the above configuration, the multi-mode laser diode can be used as the light source without increasing the manufacturing cost of the fθ optical system.

[0015] Optionally, a central axis of the laser beam incident on the polygonal mirror and an optical axis of the fθ lens are on a same plane and form a predetermined angle.

[0016] According to a further aspect of the invention, there is provided a scanning optical system which is provided with a light source including a multi-mode laser diode emitting a laser beam, a polygonal mirror that deflects the laser beam emitted by the light source, and an fθ optically system that converges the laser beam deflected by the polygonal mirror on an object to be scanned, the fθ lens being configured to suppress lateral chromatic aberration. In particular, the lateral chromatic aberration is suppressed by employing at least one of (a) a reflection surface having a predetermined power in the main scanning direction and (b) a diffractive lens structure that compensates for chromatic aberrations provided by a refractive lens structure of the fθ lens.

BRIEF DESCRIPTION OF THE ACCOMPANYING DRAWINGS

[0017] **FIG. 1 a** perspective view of a scanning optical system according to a first embodiment of the invention;

[0018] **FIG. 2** is a view, taken along a plane perpendicular to an auxiliary scanning direction, of the scanning optical system according to the first embodiment;

[0019] **FIG. 3** is a view, taken along a plane perpendicular to a main scanning direction, of the scanning optical system according to the first embodiment;

[0020] **FIGS. 4A-4C** are graphs indicating an fθ error, curvature of field and lateral chromatic aberration of the scanning optical system according to the first embodiment;

[0021] **FIG. 5** is a view, taken along a plane perpendicular to an auxiliary scanning direction, of a scanning optical system according to a second embodiment;

[0022] **FIGS. 6A and 6B** are side and front view of a first lens of an fθ lens employed in the scanning optical system according to the second embodiment; and

[0023] **FIGS. 7A-7C** are graphs indicating an fθ error, curvature of field and lateral chromatic aberration of the scanning optical system according to the second embodiment.

DETAILED DESCRIPTION OF THE EMBODIMENTS

[0024] Hereinafter, scanning optical systems according to two embodiments of the invention will be described with reference to accompanying drawings.

[0025] According to the embodiments, the scanning optical systems are to be employed in an exposure unit of a laser beam printer. The exposure unit emits a scanning laser beam which is ON-OFF modulated in accordance with an input image signal to the photoconductive drum to form an electrostatic latent image thereon.

[0026] First Embodiment

[0027] **FIG. 1 a** perspective view of a scanning optical system **100** according to a first embodiment of the invention. The scanning optical system **100** employs a multi-mode laser diode **10**. The laser diode **10** emits a diverging laser beam, which is collimated by a collimating lens **20**. The collimated laser beam is incident on an anamorphic lens **30**, which has a relatively strong positive power in the auxiliary scanning direction and a relatively week negative power in the main scanning direction. The laser beam passed through the anamorphic lens **30** is reflected by a planar mirror **31** and incident on the polygonal mirror **50** with a certain angle in the auxiliary scanning direction (see **FIG. 3**).

[0028] The beam incident on the polygonal mirror **50** is reflected by reflection surfaces **51** thereof with a first separation angel a in the auxiliary scanning direction. The reflected laser beam is incident on the fθ optical element **40**. The fθ optical element **40** is formed of transparent material having a first surface **41** which allows the beam to pass therethrough, and a second surface **42** which reflects the beam incident from the first surface **41** on its inner surface. The beam reflected by the inner surface of the second surface **42** passes through the first surface **41** again, and exits therefrom.

[0029] The second surface **42** is formed with a reflection coating of silver or aluminum by deposition so that the beam is reflected on its inner surface. The first surface **41** and the second surface **42** incline macroscopically with respect each other in the auxiliary scanning direction.

[0030] The laser beam exiting from the fθ optical element **40** proceeds toward the polygonal mirror **50** with a second separation angle β in the auxiliary scanning direction between the incident beam and the exiting beam. The beam passes above the polygonal mirror in **FIG. 1**, and forms a beam spot, which scans in the main scanning direction that is parallel with a generatrix of a cylindrical shape of the photoconductive drum **60**.

[0031] It should be noted that the positive power of the fθ optical element **40** in the main scanning direction is mainly provided by the second surface **42** which is the reflection surface. Accordingly, the lateral chromatic aberration is well suppressed, and the beam emitted by the multi-mode laser diode **10** can be sufficiently converged to form a beam spot having a sufficiently small size.

[0032] **FIG. 2** is a view, taken along a plane perpendicular to an auxiliary scanning direction, of the scanning optical system according to the first embodiment. **FIG. 3** is a view, taken along a plane perpendicular to a main scanning direction, of the scanning optical system according to the first embodiment.

[0033] In each of **FIGS. 2 and 3**, a structure of the scanning optical system from the anamorphic lens **30** to the photoconductive drum **60** is shown. In **FIG. 2**, the laser diode **10** and the collimating lens **20** are also shown. It should be noted that, in **FIG. 2** or **3**, a mirror **31** is omitted from the drawing, and an optical path between the anamorphic lens **30** and the polygonal mirror **50** is indicated as a developed path.

[0034] TABLE 1 indicates a concrete example of the scanning optical system according to the first embodiment of the invention. In the table, α denotes the first separation angle, β denotes the second separation angle, ry denotes radius of curvature of each surface in the main scanning direction, rz denotes radius of curvature of each surface in the auxiliary scanning direction (indication thereof will be omitted where the surface is a rotationally symmetrical one), d denotes a distance between adjoining surfaces on the optical axis, and n denotes a refractive index at a wavelength of 780 nm.

[0035] Surface numbers indicated in the table are assigned to the surfaces of the optical elements in the order where the laser beam proceeds. That is, surfaces #1 and #2 represent surfaces of the anamorphic lens **30**, surface #3 represents the mirror surfaces **51** of the polygonal mirror **50**, surface #4 represents the first surface **41** of the fθ optical system **40**, surface #5 represents the second surface **42** of the fθ optical system **40**, and surface #6 represents the first surface **41** of the fθ optical system **40** (i.e., surfaces #4 and #6 indicate the same surface).

TABLE 1

scanning coefficient: 135.5 α = 10.0° β = 8.0°

Surface	ry	rz	d	n
#1	−72.000	55.424	2.000	1.48617
#2	∞	—	113.000	
#3	∞	—	50.000	
#4	−265.075	∞	5.000	1.48617
#5	−231.860	TABLE 3	5.000	1.48617
#6	−265.075	∞	160.035	

[0036] The first surface **41** (i.e., surfaces #4 and #6) is an anamorphic aspherical surface which is not a rotationally symmetrical surface. The shape of the first surface **41** along the main scanning direction is expressed by a SAG X(Y) which is a function of a coordinate Y in the main scanning direction.

$$X(Y)=\frac{Y^2}{r\left(1+\sqrt{1-\frac{(\kappa+1)Y^2}{r^2}}\right)}+\sum AMpY^p \tag{1}$$

[0037] where, it is assumed that the shape in the main scanning direction passes a predetermined origin, and Y is a coordinate, with respect to the origin, of a point on the first surface **41** along the main scanning direction, X(Y) is a SAG amount which represents a distance of the point on the first surface **41** with respect to a plane tangential to the first surface **41** at the origin, r represent a radius of curvature at the origin, κ represents a conical coefficient and AMp is a p-th order aspherical coefficient (p being an integer).

[0038] The shape of the first surface **41** in the auxiliary scanning direction is an arc, whose curvature Cz(Y) at a coordinate Y in the main scanning direction is expressed by equation (2):

$$Cz(Y)=Czo+\Sigma ASqY^q \tag{2}$$

[0039] where, Czo is a curvature in the auxiliary scanning direction on the origin, and ASq represents a q-th order curvature coefficient.

[0040] The values of the coefficients AMp and ASq for equations (1) and (2) are indicated in TABLE 2.

[0041] It should be noted that the radius of curvature in the auxiliary scanning direction at the origin of the first surface **41** is infinity, and therefore, the curvature Czo is zero. Further, since the values for odd order of AMp and ASq are zero, TABLE 2 indicates the values for even order thereof. As understood from the equations, the first surface **41** is symmetrical in the main scanning direction with respect to the origin, and also symmetrical in the auxiliary scanning direction with respect to the origin since the shape in the auxiliary scanning direction is an arc.

TABLE 2

MAIN SCANNING DIRECTION		AUXILIARY SCANNING DIRECTION	
κ	0.0	—	
AM2	9.57071×10^{-04}	AS2	3.32077×10^{-08}
AM4	-6.81320×10^{-11}	AS4	-1.02051×10^{-11}
AM6	-3.84519×10^{-11}	AS6	-5.96555×10^{-15}
AM8	-9.94042×10^{-18}	AS8	1.46273×10^{-16}
AM10	-5.33698×10^{-21}	AS10	0.0
AM12	-1.13355×10^{-24}	AS12	0.0

[0042] The second surface **42** (surface #5) of the fθ optical element **40** is expressed by a SAG X(Y, Z) which is a function of Y and Z coordinates, where Y is a height of a point on the second surface **42** in the main scanning direction with respect to an origin and Z is a height of the point in the auxiliary scanning direction.

$$X(Y,Z)=\frac{Y^2+Z^2}{r\left(1+\sqrt{1-\frac{(\kappa+1)(Y^2+Z^2)}{r^2}}\right)}+\sum B_{mn}Y^mZ^n \tag{3}$$

[0043] where, the SAG X(Y,Z) represents a distance of the point on the second surface **42** with respect to an imaginary reference plane, r is a radius of curvature of the surface at the origin, κ is a conical coefficient and Bmn is a coefficient.

[0044] Each of the reference plane referred to for defining the second surface **42** and the tangential plane referred to when defining the first surface **41** is perpendicular to a predetermined reference axis, and intersection point of the reference axis and each of the first and second surfaces **41** and **42** is defined as the origin for each surface.

[0045] The values of the coefficients Bmn are indicated in TABLE 3. It should be noted that, in the auxiliary scanning direction, coefficients Bmn for terms having only a first-order component (i.e., odd-order terms) have values other than zero. Therefore, the second surface **42** is inclined, in the auxiliary scanning direction, with respect to the reference plane. In the main scanning direction, the coefficients Bmn for odd-order terms are zero, and therefore, the second surface **42** is symmetrical, in the main scanning direction, with respect to the origin.

[0046] TABLE 3 includes values for odd numbers of n, but does not include values for odd number of m since they are zero.

TABLE 3

Bmn	n = 0	n = 1	n = 2	n = 3	n = 4
m = 0	0.0	-4.7676×10^{-02}	-1.9823×10^{-03}	-2.6829×10^{-06}	1.6459×10^{-06}
m = 2	2.9399×10^{-04}	3.0589×10^{-06}	2.0803×10^{-07}	-1.8380×10^{-09}	-3.9318×10^{-12}
m = 4	3.9253×10^{-08}	4.4950×10^{-10}	-2.8244×10^{-11}	4.6055×10^{-13}	-1.6421×10^{-13}
m = 6	-1.6234×10^{-11}	-5.9046×10^{-10}	2.1719×10^{-14}	-8.1058×10^{-16}	-4.4493×10^{-17}
m = 8	1.0587×10^{-15}	2.1083×10^{-11}	9.7026×10^{-18}	4.8969×10^{-19}	1.6297×10^{-20}
m = 10	-5.8655×10^{-19}	-3.1655×10^{-20}	3.4090×10^{-21}	0.0	0.0
m = 12	8.2703×10^{-23}	0.0	0.0	0.0	0.0

[0047] The tangential plane to the first surface **41** and the reference plane for the second surface **42** are parallel to each other, and are perpendicular to the same reference axis. The first surface **41** does not incline with respect to the tangential plane, while the second surface **42** inclines, in the auxiliary scanning direction, with respect to the reference plane. Therefore, macroscopically, the first surface **41** and the second surface **42** are inclined with respect to each other in the auxiliary scanning direction.

[0048] **FIGS. 4A-4C** are graphs indicating an fθ error, curvature of field (broken line: main scanning direction; solid line: auxiliary scanning direction) and lateral chromatic aberration (wavelength difference: 2 nm) of the scanning optical system **100** according to the first embodiment. In each graph, the vertical axis represents an image height (i.e., a distance in the main scanning direction with respect to the center of a scanning range on the photoconductive drum), and the horizontal axis represents the quantity of aberration (unit: mm). Since the power in the main scanning direction is achieved mainly by the reflection surface, the lateral chromatic aberration is well suppressed.

[0049] Second Embodiment

[0050] **FIG. 5** is a view, taken along a plane perpendicular to an auxiliary scanning direction, of a scanning optical system **200** according to a second embodiment.

[0051] Similarly to the first embodiment, the scanning optical system **200** employs the multi-mode laser diode **10** and the collimating lens **20**. The laser beam collimated by the collimating lens **20** is incident on a cylindrical lens **32** which has a positive power only in the auxiliary scanning direction. The laser beam passed through the cylindrical lens **32** is deflected by the polygonal mirror **50** and incident on an fθ lens **70**, which converges the laser beam on the photoconductive drum **60** to form a beam spot thereon. According to the second embodiment, the central axis of a beam incident on the polygonal mirror **50** and the optical axis of the fθ lens are on the same plane and form a predetermined angle. With this configuration, the amount of bow generated by the fθ lens can be reduced. In contrast to the second embodiment, according to the structure of the first embodiment, the size of the scanning optical system can be made smaller.

[0052] The fθ lens **70** includes a first lens **71** located on the polygonal mirror side and a second lens **72** located on the photoconductive drum side. Further, a polygonal mirror side surface of the first lens **71** is formed with a transmissive diffraction surface DIF.

[0053] **FIG. 6A** is a side view of the first lens **71**, and **FIG. 6B** is a front view, viewed from the polygonal mirror side, of the first lens **71**.

[0054] As shown in **FIG. 6A**, the diffraction lens structure DIF has steps whose pitch is smaller at an outer portion thereof. The boundaries of the steps are, when viewed from the polygonal mirror side, formed to be a part of concentric circles as shown in **FIG. 6B**.

[0055] It should be noted that **FIGS. 6A and 6B** show exaggerated view, where the number of steps are less than the actual number, and the height of steps are larger than the actual height for the sake of brevity.

[0056] The fθ lens **70** has a simple structure consisting of only two refractive lenses. However, by forming the diffractive lens structure DIF, the lateral chromatic aberration is well compensated, the laser beam emitted by the multi-mode laser diode can be converged to a necessary size. An example of the diffractive lens structure employed in a scanning optically system and compensates for the lateral chromatic aberration is disclosed in U.S. Pat. No. 6,259,547, the teachings of which are incorporated herein by reference.

[0057] TABLE 4 indicates the numerical structure of the scanning optical system **200**. In the TABLE 2, surfaces #1 and #2 represent the cylindrical lens **32**, surface #3 represents the reflection surface **51** of the polygonal mirror **50**, surfaces #4 and #5 represent the fist lens **71** and surfaces #6 and #7 represent the second lens **72** of the fθ lens **70**. The focal length of the diffraction lens surface DIF is 5089.159 mm.

TABLE 4

scanning coefficient: 200.000

Surface	ry	rz	d	n
#1	∞	55.424	2.00	1.48617
#2	∞	—	97.00	
#3	∞	—	40.00	
#4	−153.034	—	8.50	1.48617
#5	−61.827	—	110.00	
#6	−497.023	31.077	5.00	1.48617
#7	−497.950	—	90.00	

[0058] The polygonal mirror side surface (#4) of the first lens **71** is configured such that the diffraction lens structure DIF is formed on a spherical base curve. The other surface (#5) of the first lens **71** is a rotationally symmetrical aspherical surface.

[0059] The rotationally symmetrical aspherical surface is expressed by a SAG X(h) which represents a distance from a plane tangential to the rotationally symmetrical aspherical surface at the optical axis thereof to a point thereon, whose height with respect to the optical axis is h. The SAG X(h) is expressed by the following equation.

$$X(h) = \frac{h^2}{r\left(1 + \sqrt{1 - \frac{(\kappa + 1)h^2}{r^2}}\right)} + \sum A_p h^p \tag{4}$$

[0060] where, κ is a conical coefficient, r is a radius of curvature of the aspherical surface at the optical axis, and Ap is an aspherical coefficient for p-th order term.

[0061] The values of κ and Ap are indicated in TABLE 5.

TABLE 5

κ	0.00000
A4	2.07880×10^{-07}
A6	-2.92095×10^{-11}
A8	2.10239×10^{-14}

[0062] The polygonal mirror side surface (#6) of the second lens **72** is an anamorphic aspherical surface, which is similar to the first surface (#4 and #6) of the fθ optical element **41** of the first embodiment, and is expressed by the equations (1) and (2). The values of the coefficients defining the surface #6 are indicated in TABLE 6.

TABLE 6

MAIN SCANNING DIRECTION		AUXILIARY SCANNING DIRECTION	
κ	0.0	—	
AM2	0.0	AS2	-2.56679×10^{-06}
AM4	1.07453×10^{-07}	AS4	-8.41951×10^{-07}
AM6	-5.45956×10^{-12}	AS6	5.51026×10^{-12}
AM8	2.14629×10^{-16}	AS8	6.98197×10^{-16}

[0063] The surface #7 of the second lens **72** is a spherical surface.

[0064] **FIGS. 7A-7C** are graphs indicating an fθ error, curvature of field (broken line: main scanning direction; solid line: auxiliary scanning direction) and lateral chromatic aberration (wavelength difference: 2 nm) of the scanning optical system **200** according to the second embodiment. In each graph, the vertical axis represents an image height (i.e., a distance in the main scanning direction with respect to the center of a scanning range on the photoconductive drum), and the horizontal axis represents the quantity of aberration (unit: mm). With use of the diffraction lens structure DIF, the lateral chromatic aberration is well suppressed.

[0065] The present disclosure relates to the subject matter contained in Japanese Patent Application No. 2001-388124, filed on Dec. 20, 2001, which is expressly incorporated herein by reference in its entirety.

What is claimed is:

1. A scanning optical system, comprising:

a light source including a multi-mode laser diode emitting a laser beam;

a polygonal mirror that deflects the laser beam emitted by said light source; and

an fθ lens that converges the laser beam deflected by said polygonal mirror on an object to be scanned,

wherein said fθ lens includes at least one refractive lens and a diffractive lens structure formed on at least one surface of said at least one refractive lens, said diffractive lens structure being configured to compensate for chromatic aberrations provided by a refractive lens structure of said fθ lens.

2. The scanning optical system according to claim 1, wherein a central axis of the laser beam incident on the polygonal mirror and an optical axis of said fθ lens are on a same plane and form a predetermined angle.

3. A scanning optical system comprising:

a light source including a multi-mode laser diode emitting a laser beam;

a polygonal mirror that deflects the laser beam emitted by said light source; and

an fθ optical system that converges the laser beam deflected by said polygonal mirror onto an object to be scanned, said fθ lens being configured to suppress lateral chromatic aberration,

wherein the lateral chromatic aberration is suppressed by employing at least one of a reflection surface having a predetermined power in the main scanning direction or a diffractive lens structure that compensates for chromatic aberrations provided by a refractive lens structure of said fθ lens.

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